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ORBITAL CAPTURE OF STARS BY A MASSIVE BLACK HOLE VIA EXCHANGES WITH COMPACT REMNANTS

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ABSTRACT

We propose a dynamical mechanism for capturing stars around a massive black hole (MBH), which is based on the accumulation of a very dense cluster of compact stellar remnants near the MBH. This study is motivated by the presence of ~ 10 young massive stars ($M_\star \sim 3$–$15\,M_\odot$, spectral types ∼B9V–O8V) less than 0.04 pc from the MBH in the Galactic center (GC). Their existence in the extreme environment so close to an MBH is a challenge for theories of star formation and stellar dynamics. We show that young stars, which formed far from the MBH and were then scattered into eccentric orbits, repeatedly cross a cluster of stellar black holes (SBHs), where they may undergo rare direct three-body exchanges with an MBH-SBH "binary". The interaction between two objects of comparable mass ejects the SBH and captures the star on a tight orbit around the MBH. Such captures can naturally explain some trends observed in the orbits of the young stars. We derive the capture cross-section, validate it by Monte Carlo simulations, and calculate the number of captured stars in the GC using the currently uncertain estimates of the numbers of SBHs in the inner 0.04 pc and of young stars in the inner few parsecs of the GC. We find that under favorable conditions three-body exchange can account for $\sim 25\%$ of the observed stars, mostly at the fainter end of the observed range. We discuss additional effects that possibly increase the capture efficiency. Future detections of the dark mass around the MBH and deeper surveys of the central parsecs will establish whether or not there are enough SBHs and young stars there for exchange captures to singly account for the central young stars. We estimate that there are also ~ 35 lower mass stars ($M_\star \sim 1$–$3\,M_\odot$, ∼G2V–A0V) in the inner 0.04 pc similarly captured by exchanges with neutron stars (NSs). Ongoing replacement of compact remnants by main-sequence stars (SBHs by NS progenitors, NSs by white dwarf progenitors) may regulate the accumulation of compact remnants near the MBH.

Subject headings: black hole physics—galaxies: nuclei—stars: kinematics

1. INTRODUCTION

Deep near-infrared photometric (Krabbe et al. 1995; Genzel et al. 2003), spectroscopic (Genzel et al. 1997; Eckart, Ott & Genzel 1999; Figer et al. 2000; Gezari et al. 2002; Ghez et al. 2003) and astrometric (Ghez et al. 2003; Schödel et al. 2003) observations of the dense stellar cusp around the massive black hole (MBH) in the Galactic center (GC) reveal a centrally concentrated distribution of young massive stars, $N_\star \sim 10$ stars within the central $r_\star \sim 0.04$ pc, ~ 40 within ~ 0.1 pc, spanning a mass range of ~ 3–$15\,M_\odot$ (spectral types ∼B9V–O8V) with a median mass of $M_\star \sim 10\,M_\odot$, radius of $R_\star \sim 4.5\,R_\odot$ and main sequence life time of $t_\star \sim 3\times 10^7$ yr[1]. Orbital solutions obtained for eight of the stars (Ghez et al. 2003; Schödel et al. 2003) tentatively suggest some trends in their orbital properties: a lower bound on the apoapse of ~ 0.01 pc (Ghez et al. 2003) and higher than random orbital eccentricities (Schödel et al. 2003).

None of the solutions proposed so far for the puzzle of the young stars (Genzel et al. 2003; Ghez et al. 2003) are satisfactory. These fall into three categories: exotic modes of star formation near the MBH; rejuvenation of old stars in the local population; or dynamic migration from farther out, where stars can form. Even if shock cooling of molecular gas by cloud-cloud collisions could trigger star formation near the MBH (Morris 1993), molecular clouds would either form stars or be tidally disrupted well outside of the inner 0.1 pc (Vollmer & Duschl 2001). Growth and rejuvenation by mergers (Genzel et al. 2003) are not expected to be efficient in high velocity collisions near an MBH. Tidal heating by the MBH requires that the stars approach the MBH much closer than they are observed to do (Alexander & Morris 2003). The young stars are too short-lived to have formed far from the MBH and then migrated inward by mass segregation or dynamical friction. The migration can be accelerated if the stars are associated with a massive "anchor": an extremely dense young cluster (Portegies Zwart, McMillan & Gerhard 2003; Kim & Morris 2003), a very massive binary companion (Gould & Quillen 2003), or a 10^3–$10^4\,M_\odot$ black hole (Hansen & Milosavljević 2003). However, these scenarios must assume the existence of very rare, or even hypothetical objects, or else they cannot bring the stars close enough to the MBH. Such processes may possibly explain the separate population of very massive and luminous "He stars" 0.1–0.5 pc from the MBH (Krabbe et al. 1995), which we do not attempt to model here.

Our model is based on the fact that 10^4–10^5 stellar black holes (SBHs) of mass $\sim$ 7–$10\,M_\odot$ are estimated to exist within ~ 1 pc of the MBH in the GC, where they have been accumulating by dynamical friction over the lifetime of the Galaxy ($t_H \sim 10\,\mathrm{Gyr}$) from a "collection basin" ~ 10 pc wide (Morris 1993; Miralda-Escudé & Gould 2000). Numerical simulations of the evolution of the GC (Freitag 2003) con-

[1] These are rough inferences. The separation of the young stars from the old population is uncertain since at present only the brightest star has been spectroscopically identified (Ghez et al. 2003).

firm that the SBHs sink to the center on a short timescale of a few gigayears, settle into a centrally concentrated distribution where the enclosed number scales as $N_\bullet(<r) \propto r^{5/4}$ (Bahcall & Wolf 1977), and dominate the stellar mass there.

2. STARS AND REMNANTS IN THE GALACTIC CENTER

On the ~ 1 pc scale, conditions are more favorable for star formation. Observations (Figer et al. 1999) and theoretical arguments (Morris 1993) indicate that star formation in the GC is ongoing and is significantly biased toward massive stars. Here we represent the present-day mass function (PMF) of the central few parsecs of the GC by a simple (nonunique) model that has such properties. We assume that the PMF is the product of continuous star formation at a constant rate with a Salpeter initial mass function (IMF) in the range $M_\star = 1.5$–$120\,M_\odot$, so that $\mathrm{d}N_\star/\mathrm{d}M_\star(t) \propto M_\star^{-2.35}\min[t, t_\star(M_\star)]$. Stars with $M_\star \leq 8\,M_\odot$ are assumed to evolve into $0.6\,M_\odot$ white dwarfs; those with $M_\star = 8$–$30\,M_\odot$ into $1.4\,M_\odot$ neutron stars (NSs); and those with $M_\star > 30\,M_\odot$ into $7\,M_\odot$ SBHs (consistent with the mass distribution found in black hole binaries; McClintock & Remillard 2004). The gas lost in the course of stellar evolution is assumed to be efficiently expelled from the system. Using the Schaller et al. (1992) solar metallicity stellar evolution tracks, we find that at $t = t_H \sim 10$ Gyr, the mass fraction in stars out of the total mass is 0.22, the mean stellar mass is $2\,M_\odot$ and the number fraction of young stars in the range 3–15 $M_\odot$ is $f_\star = 0.06$, with a mean mass of $\bar{M}_\star = 4\,M_\odot$ (corresponding to $R_\star = 2.34\,R_\odot$ and $t_\star = 2\times10^8$ yr). Dynamical measurements of the central gravitational potential indicate that the MBH mass is $m \sim 3\times10^6\,M_\odot$ (Schödel et al. 2003; Ghez et al. 2003) and that in the range ~ 0.5–10 pc the stellar mass distribution is well represented by a spherically symmetric power-law distribution, $\rho_\star \propto r^{-\alpha}$, with the most recent calibration giving $\rho_\star(1\,\mathrm{pc}) = 1.2\times10^5\,M_\odot\,\mathrm{pc}^{-3}$ and $\alpha = 1.7$ (R. Genzel 2003, private communication). The mass distribution and mass function translate to 1.5×10^5 SBHs born inside the collection basin (≤ 5 pc) and to 2.3×10^4 young stars inside 2.5 pc, where the enclosed dynamical mass is $3.4\times10^6\,M_\odot$, in general agreement with the observationally based PMF in the inner 15 pc of Mezger et al. (1999), scaled to 2.5 pc.

Young stars formed on the $\gtrsim 1$ pc scale will not be on eccentric orbits initially, because their progenitor clouds cannot survive the tidal field of the MBH. Over time, the stars will be scattered by gravitational perturbations. The most efficient of these, which can operate on a timescale of less than $t_\star$, are due to massive star-forming clusters (Zhao, Haehnelt & Rees 2002). One such cluster is statistically expected to exist, undetected, within a few parsecs of the MBH (Portegies Zwart et al. 2002). It is also possible, albeit speculative, that cloud-cloud collisions on the few parsecs scale could lead to rapid formation of massive stars on radial orbits.

Genzel et al. (2003) estimate that the enclosed *stellar* mass inside $r = 0.4$ pc scales as $M_\star(<r) = 2.5\times10^6(r/1\,\mathrm{pc})^{1.63}\,M_\odot$, assuming that the mass follows the star counts from ~ 1 pc to the center. However, the *total* mass distribution (stars and compact remnants) inside 0.1 pc, where the MBH dominates the potential but where the remnants dominate the extended mass, is not known (Mouawad et al. 2004). The central density of the SBH cluster depends on various uncertain quantities: the SBH mass function, the stellar IMF and formation rate, the remnant progenitor masses, and the dynamical age of the GC. A rough upper limit on $N_\bullet(<r_\star)$ can be obtained by requiring that the SBHs survive being drained into the MBH over the lifetime of the system, $\mathrm{d}N_\bullet/\mathrm{d}t < N_\bullet/t_H$, where $\mathrm{d}N_\bullet/\mathrm{d}t \sim N_\bullet/[\log(2/\vartheta_{\mathrm{lc}})t_r]$ is the scattering rate into loss-cone orbits that take an SBH into the MBH, $t_r \sim v^3/(\log\Lambda G^2\rho m_\bullet)$ is the relaxation time (assuming all the mass is in SBHs), ϑ_{lc} is the loss-cone opening angle and $\Lambda \sim 0.4N_\bullet$ is the Coulomb cutoff (e.g., Syer & Ulmer 1999). This constraint yields the relation (solved numerically),

$$\max N_\bullet(<r_\star) \sim \frac{2\log(2\sqrt{r_\star/r_s})}{3\log(0.4\max N_\bullet)}\left(\frac{m}{m_\bullet}\right)^2\frac{P(r_\star)}{t_H}\,, \quad (1)$$

where r_s is the Schwarzschild radius of the MBH and $P(r_\star)$ is the orbital period at $r_\star$.

3. THE DIRECT EXCHANGE CROSS SECTION

We estimate the efficiency of the capture mechanism with the assumption that the angular momentum distribution of the young stars has been efficiently randomized. For simplicity, orbital periods and periapses are considered Keplerian (this is reasonable inside 2.5 pc, where the enclosed mass is $\lesssim m$) and the typical orbital energy of a star is represented by its virial energy (equivalent to assuming the star was initially on a circular orbit). If the star is scattered to an eccentric orbit, it will pass by the MBH on a hyperbolic orbit relative to it, with energy (Alexander & Livio 2001)

$$\widetilde{E}_0 = +\frac{\widetilde{m}}{\widetilde{a}_0}\left[(\mu_0-1)\frac{3-\alpha}{2-\alpha} - \frac{\mu_0}{2}\right] \lesssim 0.1\,, \quad (2)$$

where a_0 is the orbital semi-major axis (SMA) and $\mu_0 m$ is the total mass enclosed within a_0 (the tilde symbol denotes quantities in dimensionless units G=$M_\star$=$R_\star$=1; in these units, the stellar binding energy is ~ 1).

A three-body encounter (Heggie 1975) is characterized by a dimensionless relative velocity $\widehat{v}_\infty^2 \equiv -\widetilde{E}_0/\widetilde{E}_\bullet$ between the incoming star at infinity and the binary barycenter, where $\widetilde{E}_\bullet = -\widetilde{m}\widetilde{m}_\bullet/2\widetilde{a}_\bullet$ is the binding energy of an MBH-SBH "binary" with SMA $\widetilde{a}_\bullet$. When $\widehat{v}_\infty \geq 1$ (a fast encounter with a soft binary), the incoming star carries enough energy to ionize (disrupt) the binary. When $\widehat{v}_\infty < 1$ (a slow encounter with a hard binary), the only possible outcomes are exchange, where the incoming star ejects one of the binary members and replaces it, or scattering, where the incoming star remains unbound. Typical three-body encounters between an $\sim 10\,M_\odot$ star and a SBH in the GC occur below the ionization threshold (Table 1). Note that the actual 2-body interaction between the star and the SBH is analogous to the high velocity exchanges studied by Hut (1983).

An exchange can proceed via two channels: direct or resonant. It is direct when the star passes within the SBH capture radius $\widetilde{r}_c \sim [(1+\widetilde{m}_\bullet)/\widetilde{m}]\widetilde{a}_\bullet$ and ejects it. In this case, the three-body analogy is justified because $r_c \ll n_\star^{-1/3}$, the mean distance between stars. It is resonant when a transient three-body bound system forms and persists for many orbits over a volume of radius $\sim a_\bullet$, until one of the masses is ejected (Hut 1993). In this case, the isolated three-body analogy is no longer valid because $a_\bullet \gg n_\star^{-1/3}$. The direct exchange cross-section, which is the relevant channel here, is smaller by a factor of $[(1+\widetilde{m}_\bullet)/\widetilde{m}]^2$ than the resonant one (Heggie, Hut & McMillan 1996) and was therefore neglected in past works on isolated three-body encounters. We derive it using the approximate equality between the binding energy of the

original and exchanged binary (Heggie et al. 1996), and we calibrate it by detailed numerical 3-body simulations (Fig. 1). In the limit $\widetilde{m} \gg \widetilde{m}_\bullet$,1 and for $1/2 \lesssim \widetilde{m}_\bullet \lesssim 2$, the direct exchange cross-section averaged over all orbital angles for a thermal distribution of binaries with SMA $\widetilde{a}_\bullet$ is

$$\widetilde{\Sigma}(\widetilde{a}_\bullet) \simeq \left(1+2A\frac{\widetilde{m}+\widetilde{m}_\bullet}{\widetilde{m}\widetilde{m}_\bullet\widehat{v}_\infty^2}\right) \times \left[B\pi\left(\frac{1+\widetilde{m}_\bullet}{1+\widetilde{m}+\widetilde{m}_\bullet}\widetilde{a}_\bullet\right)^2\right]\left[\widetilde{m}_\bullet^{-7/4}\left(\frac{\widetilde{m}_\bullet+\widetilde{m}}{1+\widetilde{m}}\right)^{1/4}\right], \quad (3)$$

where the first factor is the gravitational focusing term, the second is the geometrical term $\pi\widetilde{r}_c^2$, and the third is the phase space factors required by detailed balance arguments (Heggie et al. 1996). The best fit parameters obtained from the numerical simulations are $A\sim 0.6$, and $B\sim 0.7$.

Equation (3) describes an isolated system in which the binary has a specified SMA and in which the captured star is initially unbound at infinity. Capture by three-body exchange in the CG differs in that the stars are scattered from a finite distance and are captured by a distribution of SBHs enclosed within $r_\star$. Equation (3) is then applied by replacing $\widetilde{a}_\bullet \to \langle\widetilde{a}_\bullet\rangle \sim 1.5r_\star$, the mean SMA in a $r^{-7/4}$ cusp, and by replacing

$$\widehat{v}_\infty^2 \to \widehat{v}_0^2 \Big/ \left\{1+\frac{r_\star}{a_0}\left[\frac{3-\alpha}{2-\alpha}(\mu_0-1)-\mu_0\right]\right\}, \quad (4)$$

where $\widehat{v}_0^2 = -(\mu_0\widetilde{m}/\widetilde{a}_0)/(2\widetilde{E}_\bullet)$. The ionization threshold remains at $\widehat{v}_\infty = 1$, but now ionization implies the ejection of the SBH out to a distance $\sim a_0$, where its orbit is randomized, and not to infinity.

The number of captured stars orbiting the MBH is the product of the capture probability per passage, $N_\bullet\Sigma$, the typical lifetime of a star after capture, $t_\star/2$, and the incoming flux of young stars, $f_\star\int(n_\star q_\star/P_0)\mathrm{d}^3r/(\pi r_\star^2)$, where P_0 is the orbital period at a_0 and $q_\star = 1-(1-r_\star/a_0)^2$ is the fraction of stars on orbits that cross inside $r_\star$. The steady state number of captured young stars within $r_\star$ is then

$$N_\star = \frac{t_\star N_\bullet}{2\pi r_\star^2}\frac{f_\star}{\bar{M}_\star}\int_{a_1}^{a_2}\frac{\nu_\star q_\star \Sigma}{P_0}\,\mathrm{d}a_0\,, \quad (5)$$

where $\nu_\star$ is the stellar mass density per unit SMA.[2] The integration runs from the smallest SMA where young stars can be formed (here assumed to be $a_1 = 0.44$ pc, where a star with the virial energy is unbound to the MBH) up to $a_2 = 2.5$ pc where the Keplerian approximation is marginally valid. Stars can also be captured from orbits with $a_0 > a_2$ up to a maximal SMA, where $\widehat{v}_\infty = 1$. However, the contribution of such stars to the total is small because of the longer P_0 and smaller $q_\star$. Note that since $\widehat{v}_\infty$ increases with $a_\bullet$ and a_0, there exists a maximal radius where stars can be captured, $r_\star \lesssim 1$ pc. Beyond this limit three-body interactions result in ionization, not capture.

4. EXCHANGE CAPTURE IN THE GALACTIC CENTER

Table (1) shows the number of captured stars, assuming that SBHs born in the central 5 pc are now concentrated inside $r_\bullet = 0.7$ pc. This choice of $r_\bullet$ (e.g. Morris 1993; Miralda-Escudé & Gould 2000) implies that the central concentration of SBHs is near the drain limit (Eq. 1) and that SBHs dominate the central mass density, as expected in a dynamically evolved system (Freitag 2003). The predicted mean number of captured stars is $\sim 25\%$ of those observed. The captured stars are expected to lie mostly at the low-mass and low-luminosity end of the observed range because lower-mass stars are more numerous and live longer.

In addition to the fact that capture by exchange can account for at least some of the young stars, this mechanism can naturally explain observed trends in their orbital properties. Because r_c falls with the distance to the MBH, there exists a minimal distance $\widetilde{r}_{\min} \sim 0.8\widetilde{m}\widetilde{m}_\bullet^{1/3}/(1+\widetilde{m}_\bullet)$ where the capture radius equals the tidal radius of the SBH (Alexander & Kumar 2001). Beyond this limit, an exchange is no longer possible since the star is disrupted. Near disruption at $r_{\min}$, the tidal interaction absorbs orbital energy of the order of the stellar binding energy, so that the captured star loses most of its kinetic energy in the encounter, and $r_{\min}$ then becomes the apoapse of the new orbit. In the GC, $r_{\min} \sim 0.01$ pc, which is

[2] The spatial distribution $\rho_\star(r) = Cr^{-\alpha}$ in a Keplerian potential corresponds to $\nu_\star(a) = 3\pi 2^{-\alpha}\beta(\alpha+1,-3/2)Ca^{2-\alpha}$ (Schödel et al. 2003).

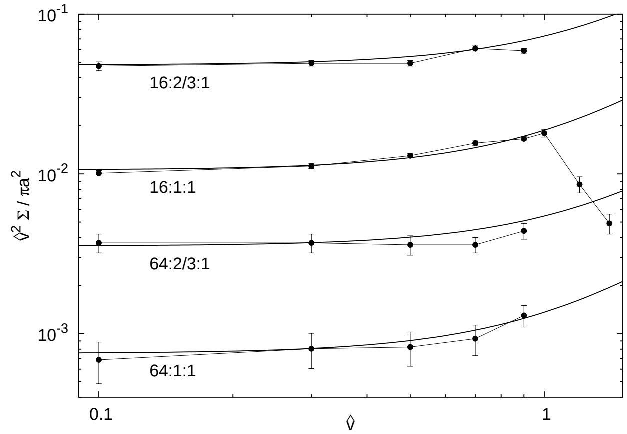

FIG. 1.— Direct exchange cross-section below the ionization threshold (multiplied by $\widehat{v}^2/\pi a_\bullet^2$) for $\widetilde{m}_\bullet = 2/3, 1$ and $\widetilde{m} = 16, 64$ as a function of $\widehat{v}$. Points with error bars are Monte Carlo estimates of the cross section (using the SIGMA3 program [McMillan & Hut 1996] of the Starlab software package by Hut, McMillan, Makino & Portegies Zwart; available at http://www.ids.ias.edu/~ starlab). Thick lines are the best-fit analytic approximation (Eq. 3). For $\widehat{v} > 1$, binary ionization competes with direct exchange, and the cross section (shown here only for $m : m_\bullet : M_\star = 16:1:1$) rapidly falls off.

TABLE 1
THREE-BODY EXCHANGE IN THE GALACTIC CENTER

Parameter	Extent of young stars, $r_\star$ (pc) 0.04	0.10
Number of observed young stars, $N_\star$	~ 10	~ 40
Number of captured young stars in $r_\star$, $N_\star$ [a]	2.4	7.7
Number of SBHs in $r_\star$, $N_\bullet$ [b]	4.2×10^3	1.3×10^4
Drain limit, $\max N_\bullet$	4.7×10^3	1.7×10^4
Enclosed SBH / stellar mass[c] ratio in $r_\star$	2.1	1.5
Mean[d] velocity at infinity, $\langle\hat{v}_\infty\rangle$	0.2	0.4
Median[e] initial SMA, a_0 (pc)	0.9	0.9

[a] For 2.3×10^4 young stars ($M_\odot = 3$–$15\ M_\odot$) inside 2.5 pc.
[b] For 1.5×10^5 SBHs of 7 $M_\odot$ within $r_\bullet = 0.7$ pc.
[c] Relative to the estimated enclosed stellar mass (Genzel et al. 2003).
[d] $\mathrm{d}N_\star$-weighted mean between a_1 and a_2.
[e] Half of the captured stars originate between median a_0 and a_2.

consistent with the observed lower bound on the apoapse of the young stars (the local relaxation time is longer than $t_\star$, so they are expected to remain on their original orbits). We note that the extraction of orbital energy can increase the capture efficiency. A rough estimate indicates a factor of ~ 2 increase in the cross-section for captures occurring near $r_{\rm min}$, where the tidal interaction is strong. This effect was not included in the results quoted in Table (1).

The numerical simulations also show that the exchanged binaries have higher than random eccentricities, even when the SBHs have a random (thermal) distribution of eccentricities. The bias becomes substantial the faster ($\widehat{v}_\infty \to 1$) and more massive ($\widetilde{m}_\bullet < 1$) the incoming star is. This property of the exchange mechanism agrees with the observed trend.

Lower mass main-sequence stars in the range $M_\star = 1$–$3\,M_\odot$ ($\sim$G2V–A0V) can be similarly captured by NSs. Dynamical simulations of the GC indicate that the central number density of NSs is $\sim 1/3$ that of the SBHs (M. Freitag 2003, private communication). We find that there are ~ 35 lower-mass stars captured in the inner 0.04 pc and ~ 110 captured in the inner 0.1 pc.

5. DISCUSSION AND SUMMARY

The efficiency of a "billiard ball" recoil depends strongly on the mass ratio of the colliding objects. The dynamical evolution of a stellar system around an MBH naturally provides a dense concentration of targets whose masses are well matched for stopping and capturing unbound young stars like those observed very near the MBH in the GC. The attempt to predict the number of captured stars is limited by the uncertainty in the mass and number distribution of the SBHs and in the number and orbital properties of young stars (spectral types $\sim$B9V–O8V) in the inner few parsecs of the GC. We show that under favorable conditions, capture can account for ~ 25% of the observed young stars.

Additional effects that were not taken into account here may increase the capture efficiency. We considered only capture by a single direct exchange in the point-mass approximation. However, a few weaker interactions may also lead gradually to capture during the star's lifetime. Further study is needed to estimate the contribution of multiple scatterings to the capture cross section. Tidal energy extraction in captures near the tidal limit also increases the capture cross section there. A possible outcome of internal mixing by a strong tidal interaction is an extended main-sequence lifetime and higher luminosity (Maeder & Meynet 2000). This would further increase the number of captured luminous stars (Eq. 5).

In the context of direct exchange capture, the stars with the smallest apoapse offer an opportunity to study the long term effects of a strong tidal interaction. Interestingly, S2, the star with the smallest apoapse, is also the brightest (Ghez et al. 2003; Schödel et al. 2003). The orbital eccentricity distribution reflects the mass ratio between the star and the SBH. Thus, a spectral determination of the masses of the captured stars together with a statistical analysis of their eccentricities can probe the poorly known mass function of SBHs. The total number of captured stars over the lifetime of the Galaxy (assuming steady state), $\sim 2N_\star t_H/t_\star \sim 3\times 10^4$ (for 40 stars of $10\,M_\odot$ in 0.1 pc), is of the same order as the number of SBHs in the inner parsec. Thus, if the dynamical friction timescale at $\langle a_0\rangle$ (where the SBHs are ejected to) is not much smaller than the age of the Galaxy, the continual replacement of SBHs by NS progenitors and of NSs by white dwarf progenitors (Fryer & Kalogera 2001) may regulate the build-up of the dense cusp of compact stellar remnants.

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